MEASUREMENT SYSTEM ID

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ELECTRICAL GROUNDING ARCHITECTURE:

DESIGN GUIDELINES FOR UNMANNED SPACECRAFT

NASA TECHNICAL STANDARD

FOREWORD

This standard is approved for use by NASA Headquarters and all NASA Centers and is intended to provide a common framework for consistent practices across NASA programs.

This standard was developed to provide electrical grounding design guidelines for unmanned spacecraft by A. Whittlesey, D. Nieraeth, and D. Shebel of the Jet Propulsion Laboratory, the California Institute of Technology.

This document is written for spacecraft system engineers, power engineers, and electromagnetic compatibility (EMC) engineers. It should be stressed that spacecraft grounding architecture is a system-level decision; all other grounding design must be coordinated with and be subservient to the system-level architecture. The grounding architecture must be established at the earliest point in spacecraft design (during definition of the conceptual block diagram); Preliminary Design Review (PDR) is too late.

The material covered in this handbook was initiated by Jet Propulsion Laboratory (JPL) personnel who have designed spacecraft for many years. Expertise was drawn from EMC, systems engineering, and power engineering. It has also been reviewed by personnel at other NASA centers.

This document assumes that there is no one single "correct" design for spacecraft grounding architecture. There have been many successful satellite and spacecraft programs from NASA, and the grounding architectures spanned the gamut from "totally correct" to "quicker and lower cost" (and higher risk). However, some design principles learned over years apply to all types of spacecraft development. This document summarizes those principles to help guide spacecraft grounding architecture design for NASA and others.

Requests for information, corrections, or additions to this standard should be directed to A. Whittlesey, Mail Code 301-466, the Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA, 91109. Requests for additional copies of this standard should be sent to NASA Engineering Standards, EL01, MSFC, AL, 35812 (telephone 205-544-4359).

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1. SCOPE

1.1 Scope. Grounding architecture, including its implementation, is an important part of overall mission success for spacecraft. The primary objective of proper grounding architecture is to aid in the minimization of electromagnetic interference (EMI) and unwanted interaction between various spacecraft electronic components and/or subsystems. Success results in electromagnetic compatibility (EMC). This document emphasizes that spacecraft grounding architecture is the responsibility of the system design organization, and all hardware elements must comply with the architecture established by the system designers. A further major emphasis is that grounding architecture must be established during the early conceptual design stages (before subsystem hardware contracts are established). The preliminary design review (PDR) time is too late.

1.2 Purpose. The purpose of this document is to provide a ready reference for spacecraft systems designers and others who need information about system grounding architecture design and rationale. The primary goal of this document is to show design choices that apply to a grounding system for a given size and mission of spacecraft and to provide a basis for understanding those choices and tradeoffs.

1.3 Applicability. This standard recommends engineering practices for NASA programs and projects. It may be cited in contracts and program documents as a technical requirement or as a reference for guidance. Determining the suitability of this standard and its provisions is the responsibility of program/project management and the performing organization. Individual provisions of this standard may be tailored (i.e., modified or deleted) by contract or program specifications to meet specific program/project needs and constraints. The document is specifically intended for application to NASA unmanned spacecraft. Other spacecraft development efforts can benefit to the degree that they are similar in their mission.

1.4 Constraints. This document does not cover personnel safety (such as the National Electrical Code) or regulatory compliance (such as Federal Communications Commission regulations).

There is very little coverage of grounding of structure bonding (bonding of non-electrical elements). There is a short bonding section (ref. 3.4) that refers to an appropriate document.

There is little coverage of specific design details, in order to limit the size of this document. Examples are treatment of small nanovolt signals present in instrument detectors, or specific lengths and wire types for grounding purposes. For these and other implementation details refer to other documents, or consult with the local Electromagnetic Compatibility organization, Power organization, or other local knowledgeable design persons.

2. APPLICABLE DOCUMENTS

2.1 <u>General</u>. The applicable documents cited in this standard are listed in this section only for reference. The specified technical requirements listed in the body of this document must be met whether or not the source document is listed in this section.

2.2 <u>Government documents.</u>

2.2.1 <u>Specifications, standards, and handbooks</u>. The following specifications, standards, and handbooks form a part of this document to the extent specified herein. Unless otherwise specified, the issuances in effect on date of invitation for bids or request for proposals shall apply.

DEPARTMENT OF DEFENSE

MIL-B-5087B   -   Bonding, Electrical, and Lightning Protection, for Aerospace
                       Systems, Rev. B, Interim Amendment 3, December 24, 1984

MIL-STD-1553B   -   Digital Time Division Command/Response Multiplex Data Bus
                       Notice 3, January 31, 1993

MIL-STD-1576   -   Electroexplosive Subsystem, Safety Requirements and Test
                       Methods for Space Systems, July 31, 1984

MIL-STD-1773   -   Fiber Optics Mechanization of an Aircraft Internal Time Division
                       Command/Response Multiplex Data Bus, Notice 1, October 2, 1989

(Unless otherwise indicated, copies of the above documents are available from any NASA Installation library or documentation repository.)

2.3 <u>Order of precedence</u>. Where this document is adopted or imposed by contract on a program or project, the technical guidelines of this document take precedence, in the case of conflict, over the technical guidelines cited in other referenced documents.

3. DEFINITIONS

3.1 Acronyms used in this standard.

A	ampere
ac	alternating current (greater than zero frequency)
ACS	attitude control subsystem (sometimes called Attitude Determination and Control System - ADCS)
COTS	commercial off-the-shelf
C&DH	command and data handling (sometimes called Command and Data Management System - CDMS)
dc	direct current (zero frequency)
EED	Electro Explosive Device (squibs; pyrotechnic devices)
EMC	electromagnetic compatibility
EMI	electromagnetic interference
end-circuit	as used in this document, end-circuit refers the transmitting or receiving circuit that acts as an interface to cabling and another subsystem.
GSE	ground support equipment
H-field	magnetic field
I/F	interface
JPL	Jet Propulsion Laboratory
kΩ	kilohm
kg	kilogram
M	million
m	meter
MΩ	megohm
mA	milliampere
MHz	megahertz
MIL	military
N/A	no applicable
PDR	preliminary design review
pF	picofarad
PWR	power subsystem
pyro	pyrotechnic
RF	radio frequency
RFS	radio frequency subsystem
RIU	remote interface unit
RTG	radioisotope thermoelectric generator
Rtn	return

S/C	spacecraft
SPG	single-point ground
STD	standard
str	structure
VME	Versa Module Euro card (bus standard)
V	volt
W	watt
<	less than
>	greater than
µF	microfarad

3.2 Definition of Grounding Architecture. This document focuses on providing an appropriate zero-potential reference system, for signals and power, implemented in a way that controls electromagnetic interference (EMI). This section introduces and defines concepts and nomenclature used in this document. Simple illustrations are used here; Section 4 provides greater details. The ground referencing system must not only be a dc voltage reference but an ac zero-potential system for deliberate high-frequency signals and incidental high-frequency noise, such as noise caused by dc-dc switching power converters, which are common in modern spacecraft.

This document emphasizes grounding at the system level rather than at the subsystem level. Figure 1 shows a sample spacecraft, with radio frequency subsystem (RFS), attitude control subsystem (ACS), and a power subsystem (PWR). Other subsystems are omitted for clarity. A "spacecraft" consists of the flight hardware (as contrasted with the nonflight support equipment). Many of the following drawings show subsystems only, with the spacecraft frame (chassis) assumed but not shown.
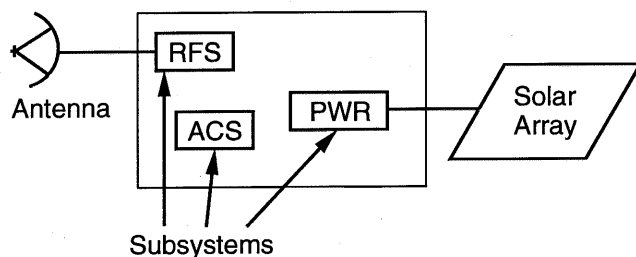

FIGURE 1. Model Spacecraft With Subsystems

Although the emphasis is at the spacecraft or system level, if a single assembly or experiment is relatively large, it also could be considered as a system, and the grounding architecture considerations discussed here could be applied to it separately. Figure 2 shows some drawing nomenclatures used in this document.
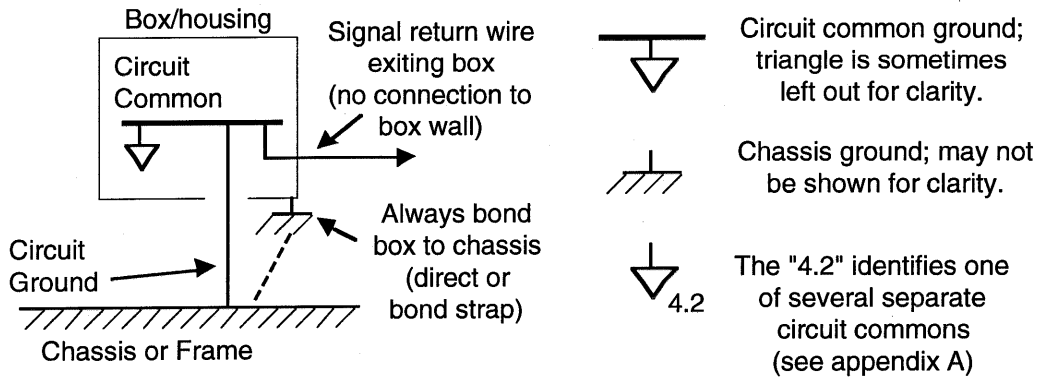
FIGURE 2. Drawing Nomenclature/Key

Isolation of grounds is an important concept. Isolation means the net dc and ac extraneous or noise current is substantially reduced (the best isolation is no noise current whatsoever) in the isolated interface. If there is a dc signal ground connection between two assemblies and they each also have a separate wire ground to chassis, their signal interfaces are not isolated from each other. Figure 3 illustrates isolation of grounds between two subsystems and lack of isolation (permitting a ground loop). Signal return current can flow both in the return wire as well as through the chassis ground connections. An example of a dc isolated interface between assemblies is a transformer used to transmit ac power; there is no dc path between the assemblies.

Ground loops can be troublesome because they can both radiate and receive magnetic field noise. AC magnetic field noise can couple into and disturb other circuits. DC magnetic fields can disturb onboard dc magnetometers. The key to minimizing the effects of ground loops is to minimize the enclosed area around which current flows. Ideally, every power and signal interface circuit will have 100 percent of its current (over all frequencies) return on a dedicated return wire in close proximity to the outgoing power or signal wire.
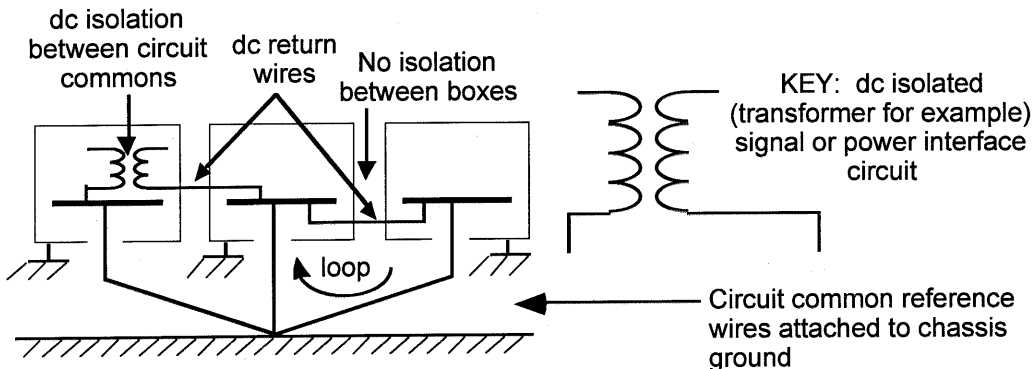
FIGURE 3. DC Isolated Ground and Not Isolated Ground

It is important to understand that the lines (wires) connecting the subsystem common to the chassis actually consist of a series resistance, a series inductance, and various capacitances to nearby objects, all of which affect the performance of the grounding architecture. If the currents or voltages in question are at higher ac frequencies, the inductance and capacitance may become significant parameters that affect the quality of the ground. This document does not

focus on these details, (but often 1 megahertz is used as the threshold of high frequencies in this context.). For a good ground at higher frequencies, shorter wire lengths are better.

Isolation methods are discussed in more detail in 4.3.

      3.3 <u>Types of Grounding Systems.</u> The two principle types of grounding systems are the single-point ground (SPG) and the multiple-point ground (see figures 4 and 5). There are numerous other similar terms used for these concepts. Note that sometimes the actual implementation may negate the intended effects. The single-point ground in figure 4 may be interpreted literally to mean that all circuit commons are grounded by means of wiring to one single point on the chassis. Note the isolation of grounds (circuit commons) between assemblies, so that there is one and only one dc ground reference path for each assembly. This is sometimes called a "star" ground because all ground wires branch out from the central point of the star. Inductances of long wires and higher frequencies can negate the adequacy of the ground to the degree that the assembly may no longer have a zero potential reference with respect to chassis. See figure 6 for a better implementation.

Isolation between assemblies.
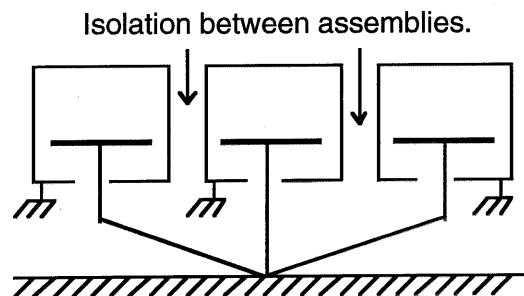
FIGURE 4. <u>Single-Point "Star" Ground</u>

Figure 5 shows a multiple point (multi-point or multi-path) ground arrangement. Note that each circuit common is grounded directly to the chassis and also grounded indirectly to the chassis via the connections to the other assemblies. This is typical for radio frequency (RF) subsystems but should not be used for video or other signals containing low frequencies [less than roughly 1 megahertz (MHz)].

No isolation between assemblies.
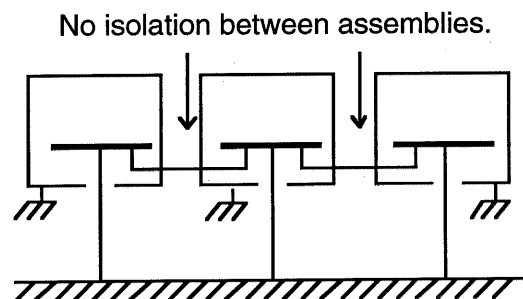
FIGURE 5. <u>Multiple Point Ground</u>

Figure 6 shows a better chassis reference ground system. Each assembly has one and only one path to the chassis (the zero voltage reference) and there are no deliberate structure currents. Compared to the star SPG of figure 4, each ground reference wire is short, providing minimum ac impedance between each circuit common and chassis. The important points are that each electronic item has one and only one path to chassis, and there is no deliberate chassis current. Also, all subsystems have a common dc voltage reference potential (the interconnected

structure). This grounding architecture is typical for a modern spacecraft that pays special attention to grounding architecture, isolation of interfaces, and minimized structure currents. Note that SPG properly means that each electrical and electronic element has only a single path to its ground point, in contrast to the improper idea that SPG means forcing all chassis grounds to be physically connected to one single point.
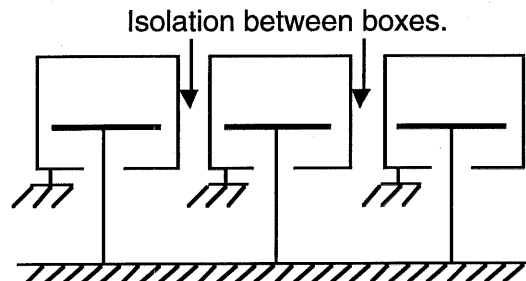
FIGURE 6. Multiple, Single Reference Ground System

Figure 7 shows a floating (isolated) ground system (generally not desirable). While systems are usually ground referenced in some manner, there is no theoretical reason why an assembly's circuit common needs to be chassis referenced. However, practical considerations dictate that at least a static bleed resistor be present, even if isolation from chassis ground is designed into the subsystem/system (chassis isolated circuit commons are vulnerable to noise pickup through parasitic paths). Note that an isolated ground system is not in compliance with man-rated systems or the National Electrical Code.
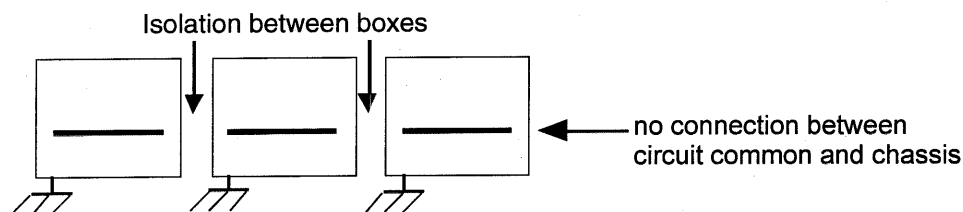
FIGURE 7. Floating (Isolated) Grounds

Figure 8 shows a daisy-chained ground system.   This is a poor practice in general, and it is shown only to emphasize that it should not be done. Shared return wires cause common mode voltage differences (circuits "talk" to each other through common mode impedance coupling). It may be tolerable if it is done within the confines of one responsible entity, such as an attitude control subsystem, and that subsystem provides the box-to-box wiring. If it is permitted for separately built assemblies that are later integrated together, unpredictable behavior may occur.
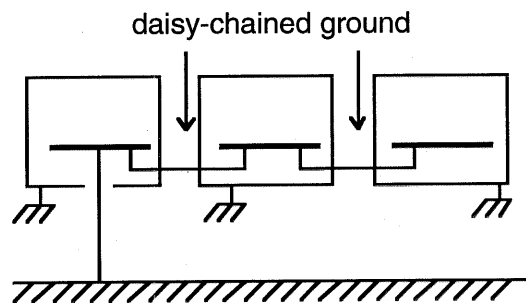
FIGURE 8. Daisy-Chained Ground System (Not Recommended)

3.4 <u>Bonding of Structural Elements.</u> Bonding does not mean the same as grounding, but the two words are often used in similar context. Bonding refers to low-impedance connections of structural and other conductive elements of the spacecraft that do not deliberately carry electrical currents. Good bonding provides a uniform near-zero volt reference plane at all frequencies for the electrical system returns. MIL-B-5087B has been the normal bonding standard and is a recommended reference. Bonding of all chassis elements is essential to provide a common voltage reference point (nearly equal) for all of the various grounded subsystems.

3.5 <u>General Comments: Floating Circuits; Test Verification.</u> In general, it is a poor idea to permit floating electronic elements. To prevent floating elements (and wiring which may float when switch contacts are open), a static "bleed" resistor [perhaps 5 megohm] to the chassis can be hard wired into the circuitry for any circuit that might float when not mated to other units.

It is desirable to make all explicit requirements testable. To verify isolation of isolated end-circuits, it is a simple matter to use a common ohmmeter, probing into the appropriate connector pin (with a breakout box or other pin-saver device as a means of access to the pin). Capacitance to the chassis can be measured with a capacitance meter at the same time. Use of specific voltages, etc., to avoid test ambiguities is not discussed in this document.

One design feature for verifying that there is a single path to ground is to have the subsystem's signal-point ground reference routed out through a connector pin, then returned into the subsystem and to chassis via a jumper in the mating connector of this design. This design feature permits verification of both the isolation and the grounding. A disadvantage of having the grounding implemented in the mating cabling is that it requires the cabling be built properly and also be verified.

4. GROUNDING ARCHITECTURE REQUIREMENTS/SELECTION CRITERIA

It is a requirement that system designers understand the following grounding design choices and have reasons for their selected grounding architecture.

4.1 <u>Size of Spacecraft.</u> The best grounding system is a single reference ground per figure 6, or its equivalent. This is not always practical and is not always necessary. The best determinant of the grounding method required is the size and complexity of the spacecraft, as shown in Table I. When using Table I, note that the spacecraft size depends on a majority of the listed parameters. It is okay if a few parameters don't match. For example, the EMC needs of science instruments on an otherwise small spacecraft may dictate implementation of large/complex spacecraft grounding methods.

The reason that size is an appropriate criterion for choice of grounding schemes is both technical and practical. Technically, smaller spacecraft have smaller distances between hardware, and non-optimal grounding may not cause as much trouble as it may on a larger spacecraft. Practically, providing electrical isolation at all interfaces costs resources (design time, parts, volume, mass, etc.) that smaller programs may not be able to afford.

After deciding on spacecraft size per Table I, refer to 4.2 for applicable details of appropriate spacecraft grounding architecture.

TABLE I. <u>Spacecraft Grounding Criteria Based on Spacecraft Size. †</u>

Parameter	Large/complex	Medium	Small/simple
Size/diameter	>3 meter	1-3 m	<1 m
Mass	>2000 kilograms (kg)	200-2000 kg	<200 kg
Schedule	>3 years (36 months)	18 months - 3 years	<18 months
Power	>800 watts (W)	200-800 W	<200 W
Cost	>$1000 million (M)	$100M-1000M	<$100M
EMC needs	Very sensitive to noise; quiet science platform*	-	Insensitive (motors, etc.)*
Reliability classification	Highest	Medium	Demonstration missions
Examples	Voyager, Galileo, Hubble, Cassini, EOS	TOPEX/Poseidon, GOES, AXAF, SIR-C, Magellan	Clementine, VME bus, New Millennium, "one-box" S/C

* Low field dc magnetometers or low-frequency E-field and H-field sensors would dictate using large spacecraft design principles.

† Some of the example spacecraft use grounding schemes other than recommended in this standard, and have had (may have) problems.

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4.2 Specific Implementations. Grounding can be separated into the following nine functional areas (each of which is illustrated in figure 9):

(1)   Single or multiple voltages from the main power distribution system
(2)   Power bus single fault isolation resistance (impedance)
(3)   Power sources (battery, etc.)
(4)   Power users (interface with power bus)
(5)   Command, data, telemetry, and signal interfaces
(6)   Attitude control subsystem (often needs special treatment)
(7)   RF interfaces
(8)   Pyrotechnic (pyro) firing unit
(9)   Other and Special cases

(3) Power Sources

(1) Power Conditioning/ Distribution System

(4) Power User (Load) Interfaces

Solar array, RTG, etc.

R (2) Fault isolation resistance.

Conversion, regulation, distribution, etc.

More users . . .

1, 2, 3, & 4. Power Distribution Interface Grounding

Isolated signal interface

1553B (e.g.)

Standard data bus interface

1553B (e.g.)

(5) Command, Signal, and Data Interface Grounding

FIGURE 9. Hardware Issues for Spacecraft Grounding Architecture (Sheet 1 of 2)

ACS sensors and loads:
Earth sensors, sun
sensors, gryoscopes,
inertial reference units, star
sensors, rockets,
thrusters, torquer bars,
reaction wheels, etc.

ACS elements are located on
the same gound tree because
ACS elements have many
electrical interfaces and share
a single power supply.

(6) Attitude Control System Interfaces

Coaxial returns at
chassis ground

Antenna
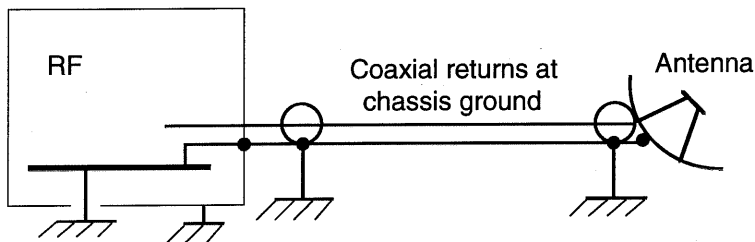
RF circuit common is multipoint
grounded for performance
reasons. There is no way to
isolate high frequencies from
chassis ground.

(7) Radio Frequency Interfaces

Shield
bonded at
both ends

Squib

Shield grounded at both ends
to extend Faraday Cage over
EED wiring.

Isolation
impedance

(8) Pyrotechnic Firing Unit

User-determined
grounding scheme
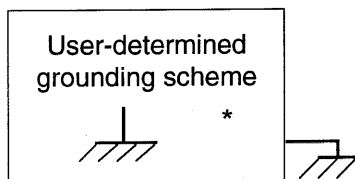
Instruments with low-level
signals, boom mounted, science
instruments, electric propulsion,
etc.

* requires approval
by EMC Engineer

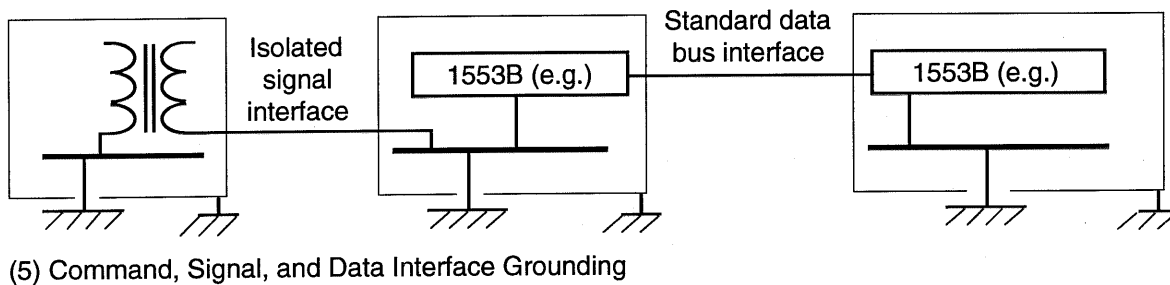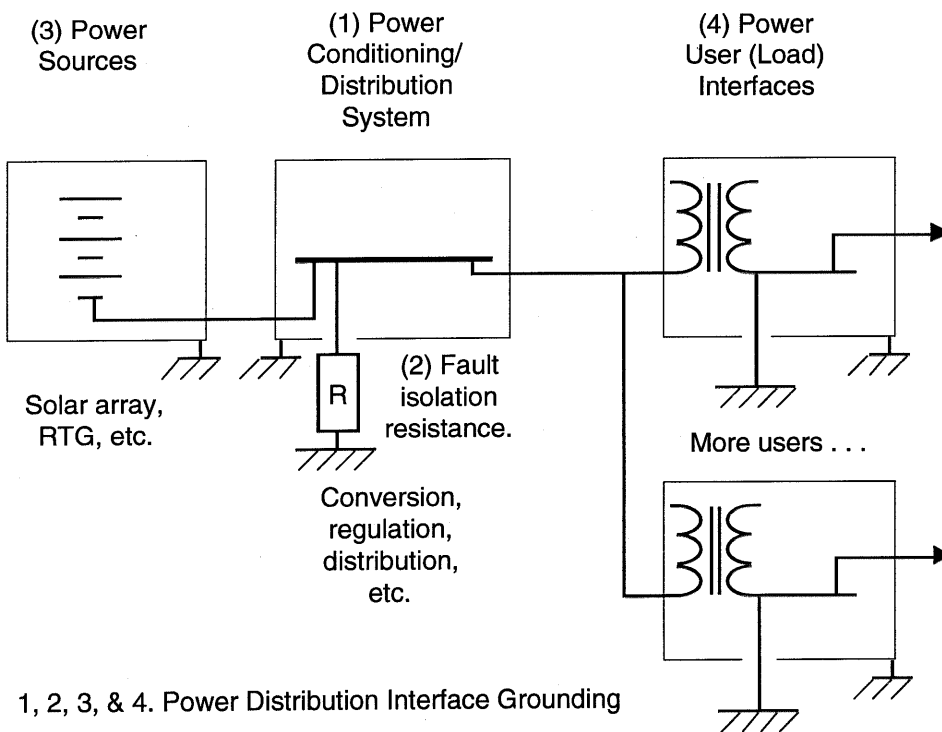(9) Other Special Cases, Needing Special Interface Grounding Treatment

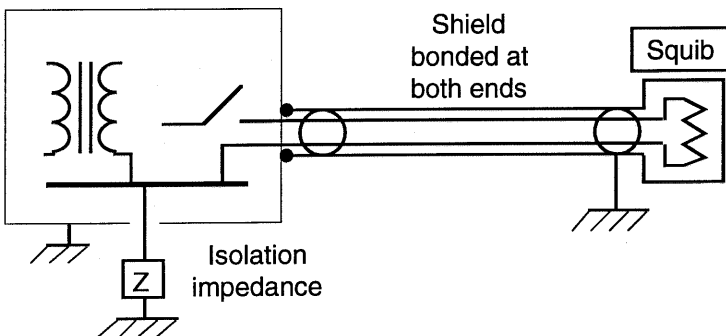FIGURE 9. Hardware Issues for Spacecraft Grounding Architecture (Sheet 2 of 2)

Table II summarizes the grounding selection issues and recommendations as keyed to the three spacecraft sizes (degree of grounding control). Paragraphs 4.2.1 through 4.2.9 provide further discussion of these nine grounding issues.

TABLE II. Spacecraft Grounding Architecture Selection Issues and Recommendations

Hardware / Interface Issue	Large / Complex Spacecraft (3)	Medium Spacecraft	Small / Simple Spacecraft	Comments
1. Power distribution system; single or multiple voltages to user loads	Single dc voltage to user loads	Single dc voltage to user loads	Permit multiple voltages to user loads	Prefer using single dc voltage to loads; small can use multiple; for example VME bus/backplane
2. Ground fault isolation of main power bus	Isolate primary power return from chassis (Note 2)	Isolate primary power return from chassis	Permit non-isolated; permit chassis currents if EMC allows	Prefer fault isolation and low chassis currents
3. Power sources (solar array, battery, RTG) grounding to chassis	Isolate the elements; provide ground referencing at power electronics assembly	Isolated	Isolated	Usually easily isolated
4. Power users (subsystem/ load); isolation from power distribution system	Power input (primary to secondary) isolated at user/load	Power input (primary to secondary) isolated at user/load	Isolation is preferred	Commercial off-the-shelf dc-dc converters often provide power isolation as-bought
5. General interface signal circuits (command, signal, and data, etc.) grounding/ isolation	• All signal interfaces between subsystems are isolated • RS-422, 1553 bus, etc., are permitted	(Note 1)	Direct, non-isolated subsystem interfaces permitted	
6. Attitude control elements, including propulsion	All interfaces isolated; referenced at central ACS electronics assembly.	(Note 1)	In small S/C, ACS and C&DH system might be integrated	Attitude control needs special attention because of the many remote sensor elements
7. RF interfaces	Multi-path	Multi-path	Multi-path	RF signals need multipoint. (Non-RF I/F's treated per issue 5)

TABLE II. Spacecraft Grounding Architecture Selection Issues and Recommendations
(Continued)

Hardware / Interface	Large / Complex Spacecraft	Medium Spacecraft	Small / Simple Spacecraft	Comments
8. Pyro firing unit	Isolated firing electronics	Direct energy transfer	Direct energy transfer	Isolation for pyro ground fault concerns
9. Other special (boom mounted, science instruments, slip rings, electric propulsion, plasma experiments)	Generally provide ground strap down dielectric boom to give good chassis reference; route separately from signal cabling			So unique that it is hard to generalize what to do; must be handled on an individual basis

NOTES:
1. If the cell is blank, it means there is no specific recommendation. This is frequently the case for the Medium Spacecraft, where the choice may be toward the isolated or the multipoint design at the system designer's discretion.
2. Note that high side (+) short to chassis won't have large currents if return (-) is isolated.
3. Large/Complex Spacecraft entries list the best/most desirable (but usually most costly) design practices.

4.2.1 Main Power Distribution System: Single or Multiple Voltages. The first consideration of the spacecraft grounding architecture is whether the main power distribution system delivers a single voltage to user loads or whether the central power distribution system provides all the voltages needed by user loads. The single voltage system (often 28 volts) is more common on larger spacecraft.

A single voltage simplifies maintenance of a single reference ground system. Each user load is responsible for both the dc-dc power conversion and the isolation from primary bus to the secondary voltages used by the subsystem. This is the preferred system and is recommended.

The multiple voltage distribution system is more easily used in a small spacecraft environment; for example, when all electronic subsystems are located on boards in a single box such as a Versa Module Euro card (VME) backplane configuration. A corollary of this system may be that signal and power interfaces are not isolated from each other. With short distances and compact electronics, this may not cause electromagnetic interference problems. They can still be dc isolated from the chassis for fault isolation (4.2.3).

4.2.2 Grounding to the Chassis. A very important decision is whether to ground the power system return wire to the chassis. Having the return wire grounded directly to the chassis is easy to do. Such a ground is generally implemented directly to the chassis near the power conditioning/distribution system (with a short wire/strap). This reduces the possibility of common mode noise at the users. It also reduces the magnitude of noise radiated from the power system wiring, especially on spacecraft that have highly sensitive experiments measuring fields and charged particles.

However, having the return wire grounded to the chassis permits a single unfused fault from the high side to the chassis to destroy the mission. This has been the cause of several mission failures (see Table V). For that reason, it is strongly recommended that the power return be isolated from the chassis by some modest impedance, high enough to limit current in case of a fault but low enough to provide a stable reference (see the following paragraph). If the power system is isolated from the chassis, all items attached to the power bus must also be isolated from the chassis (paragraphs 4.2.3 and 4.2.4). Note that if this design (soft grounding) is implemented, there is the possibility of greater power bus common mode noise, and power users should have greater common mode noise immunity. An alternate approach would be to bypass the isolation impedance with a capacitor. Such extra requirements are considered to be a tolerable side effect when balanced against the greater advantage of tolerance to high-side shorts to the chassis.

If the power system is hard grounded to chassis, it is necessary to ensure that unfused power shorts to chassis are not credible failure modes by design (e.g., double insulation), inspection, and/or test.

Isolation of the power return from the chassis (if implemented) only needs to be a moderate amount. For instance, isolation of 2 kilohm (kΩ) limits chassis currents to milliamps (28 volt)/ 2 kΩ equals 14 milliampere (mA); 0.39 W). This keeps the power return close to chassis potential but prevents loss of mission.

A more complex solution is to have a direct path to the chassis SPG through an appropriately sized fuse or circuit breaker that is paralleled by a current-limiting resistor as previously described. This permits solid power system grounding for common mode noise reduction, prevents total failure in the event of a power system high-side short to the chassis, and still has a soft reference to chassis after such a failure. For this to work, all main power bus loads must have been designed to be dc isolated from the chassis.

The Cassini spacecraft uses a balanced floating ground system for primary (30 v) power (Appendix A). Both high (+) and return (-) wires are referenced to chassis through 2 kΩ resistor.

    4.2.3 <u>Power Sources.</u> Solar arrays, batteries, and other power sources are normally electrically dc isolated from the chassis as manufactured. In order to maintain a single ground reference system, it is convenient to leave them isolated. Even in a multipoint grounded spacecraft, there is little need to deliberately ground the power sources.

One special situation is radioisotope thermoelectric generators (RTG's). Their nuclear radiation may degrade the insulating materials inside the generator (over many years), leading to shorts and/or leakages within the generator case. For this reason, designers of power systems with RTG's should consider power wiring isolation (no hard grounding of the return wires to the chassis) to reduce the effects of RTG case leakages. Isolation of the RTG case from the spacecraft chassis can also be helpful.

Another special situation is space plasma considerations. Solar arrays can leak power through the conductivity of space, due to the ions and electrons in space plasmas. The higher the solar array voltage, the more the leakage possibility. At higher voltages, (as low as 200 V on a positive grounded array and as low as 100 V on a negative grounded array) arcing may occur. If high-voltage solar arrays are planned in low-Earth to geosynchronous orbits, floating the array may become very important (do not chassis reference the power leads to the solar array).

4.2.4 <u>Power User Load Isolation From Power Distribution System.</u> If power returns are not isolated at the user loads (verify by ohmmeter measurement from power input leads to chassis), there can be ground currents in the spacecraft chassis. Power wiring isolation is usually specified to be 1 megohm (MΩ) dc. Sometimes an ac isolation limit, such as no more than 0.1 microfarad (μF) capacitance (from low side to chassis or from high side to chassis), is also specified to control higher frequency current loops. Note that isolation really means limiting current flow. The recommended 1 MΩ would then mean that less than 28 mA dc to the chassis is permitted per subsystem (28 V bus assumed).

When commercial-off-the-shelf (COTS) isolated dc-dc power converters are made part of the original subsystem design (interfacing with the spacecraft dc power bus), isolation is a relatively low-cost requirement. For this reason, it is recommended that most spacecraft be designed so that all user loads are isolated from the main dc power bus.

Isolation should be verified by measurement of all user loads.

4.2.5 <u>General Interface Circuits (Command, Signal, Data, etc.).</u> If the systems designer has chosen to have a spacecraft grounding system that is totally isolated across all interfaces, then all signal circuits (command, signal, and data, etc.) must be isolated. Note that only one end of an interface (sending or receiving) needs to be isolated.

A recommended requirement for isolation of signal interfaces is 1 MΩ and 400 picofarad (pF). That is, a measurement from either a signal wire or its return to chassis should measure greater than 1 MΩ, and there should be less than 400 pF of capacitance to the chassis. For signals that share a single return wire, the requirement for the return line may be eased to a per circuit basis (for two circuits with a shared return, the impedance from return wire to the chassis should be greater than 0.5 MΩ, and the capacitance from return wire to the chassis should be less than 800 pF, etc.).

Standard differential interface driver receiver pairs (e.g., the unidirectional RS-422 or the bi-directional MIL-STD-1553B bus circuits) generally are designed so that there are low structural ground currents. For that reason, such circuits are permitted per this document when interface isolation is specified. Remember, however, that the interface may violate the isolation needs when the circuits are unpowered. There may be sneak paths in the driver or receiver chip that permit ground currents to flow when the chip is unpowered. Also, these kinds of circuits have less immunity to common mode noise than isolation devices such as transformers or optical isolators.

If a high degree of isolation is required between subsystems that are already designed, an add-on assembly (sometimes called a remote interface unit, or RIU), can be used to accept the subsystem's signals and dc isolate individual circuits to the interfacing subsystem.

4.2.6 <u>Attitude Control Elements.</u> The attitude control subsystem presents practical difficulties for an optimal grounding system implementation. This subsystem often consists of one or more remote sensing units, one or more remote hardware elements for adjusting spacecraft orientation, and a central control assembly. If these hardware elements are bought as COTS equipment from various vendors, their signal and power interfaces may not comply with the selected spacecraft grounding architecture.

The solutions to these unique dilemmas cannot be resolved in this document. Isolation may be achieved by specifying isolation from the vendor, by designing an external isolating interface unit, or by designing isolating interfaces into the central control assembly. Another solution is to

use COTS hardware and accept any resulting chassis ground currents. In this case, one should quantify any effects on EMC or reliability.

4.2.7 RF Interfaces. RF signals usually have frequencies so high that the $\lambda/20$ criterion (one twentieth of a wavelength) would dictate that grounding be done within a few centimeters or less. Because this is a practical impossibility, most RF signals employ the multipoint ground scheme. If dc isolation is essential in an RF system, the RF ground can be achieved by capacitors.

Note that the non-RF interface circuits within RF subsystems must be isolated like general interface signal circuits in order to maintain an isolated grounding architecture. Therefore, the analog and digital systems inside RF units should be physically and electrically separated from the RF sections as much as possible (with RF chokes for example), starting with the initial design.

4.2.8 Pyro Firing Unit. Pyro firing units may need special treatment if the most conservative design is used. The greatest threat to be dealt with is the phenomenon called pyro ground-fault currents. Chassis currents as great as 20 ampere (A) may occur during pyro firing events. The ground fault current is caused by a short circuit from the positive pin to the chassis through the conductive hot plasma of the powder charge, and it continues like the arc of an arc welder. This may occur in 25 percent of the firings. In a direct-energy transfer system (pyros switched directly from the main battery bus) that is not isolated by a deliberate turn-off switch, the ground fault current could continue indefinitely when fired by a battery. The ground fault current could cause magnetic field noise coupling into nearby sensitive circuits or a near total power loss. This mechanism is compatible with several spacecraft anomalies and failures listed in Table 5..

To prevent pyro ground-fault currents, the pyro firing unit must be electrically isolated from the chassis by some means. One solution (if the main power bus is not already isolated) is a power converter that isolates the pyro firing unit from both the dc power bus and from the chassis as shown in figure 8 (panel 8). Other solutions are a separate isolated battery, a capacitor discharge subsystem resistively isolated from the main power bus on high side and return, or use of an isolation relay.

Isolation of the pyro firing circuit is not necessary if it can be ensured that all critical interface circuits are so well-designed that they are not sensitive to electrical noise or if the circuitry is software-tolerant to transient signals.

MIL-STD-1576 is a commonly required reference, defining many aspects of pyro design, including special shielding and grounding requirements for range safety.
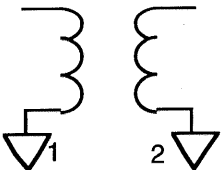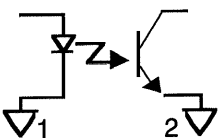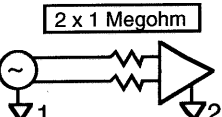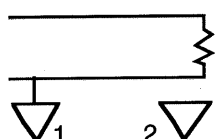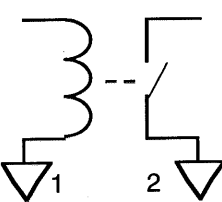
4.2.9 Other Special Items: Special Items and Cable Overshields. There are other interface situations that arise from special items in the design of a spacecraft. These include but are not limited to boom-mounted hardware, science instruments, slip rings, electric propulsion subsystems, and plasma experiments. For various reasons, the designers may not wish to isolate these items, or there may be special grounding requirements. The hardware owners know best what their needs are, and the local grounding design must be tailored for each of them.

Shield grounding is an important consideration. For intersubsystem cables with an overshield for EMC purposes, the shield should be grounded at both ends at the entry point to the subsystem/assembly. A 360 degree EMC backshell connector is preferred in this application.

In all these special circumstances, the hardware owner will benefit from a well-thought-out spacecraft electrical and electronic grounding scheme at the outset of the program. Working out the hardware owner's special needs will be easier if the other parts of the spacecraft grounding architecture have been designed in a clear and consistent manner.

4.3 Interface Isolation Circuits. In order to maintain the integrity of a ground referencing scheme, electrical isolation must be maintained across all interfaces (power, signal, command, and data). Isolation means that little or no current flows in the structure path. Table III shows examples of totally isolated circuits, and Table IV shows circuits that provide a lesser degree of isolation. Of course, totally isolated interface circuits are preferred, but the Table IV circuits are better than no isolation at all.
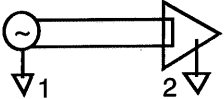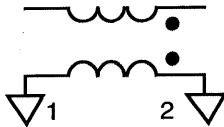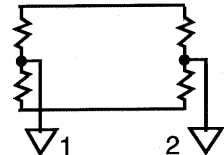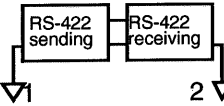
TABLE III. Totally Isolated Circuits (Hard Isolation)

TYPE	SCHEMATIC	ADVANTAGE	DISADVANTAGE	COMMENTS
Transformer		Isolation, transmits differential signals	Large, heavy, costly, limited frequency range; interwinding capacitance	Examples: 1553 data bus, clock interfaces
Optical coupling		Wide freq range, small, rejects common mode noise	Power consumption, linearity, radiation hardness	MIL-STD-1773 for example
Isolated analog op-amp	2 x 1 Megohm	Easy to implement. Power OFF isolated	Low bandwidth extra part count	
Remotely referenced (e.g., temperature transducer)		Simple	Electrical insulators are not good thermal conductors	Commonly used
Relay (coils to contacts)		Excellent dc and ac isolation	Shorter life, low-frequency response, large, binary only; high stray capacitance in power switching relays	

Note that in each of these devices, the input and output are isolated from each other by a high dc impedance; usually 1 MΩ or more. AC isolation generally deteriorates at frequencies above 1 MHz. Because of stray capacitances that do not show on the schematic, this is particularly true with the operational amplifier as its common mode rejection ratio parameter decreases with increasing frequency.

When using isolated end-circuits in high-frequency applications, it is important to be aware of parasitic reactive paths, such as interwinding capacitance in a transformer or distributed packaging capacitance as in remotely referenced circuitry.

TABLE IV. Partially Isolated Interface Circuits (Soft Isolation)

TYPE	SCHEMATIC	ADVANTAGE	DISADVANTAGE	COMMENTS
Normal analog op amp; differential amplifier		Easy to implement	Not isolated when op-amp is off; common mode noise rejection may be a problem	
Common mode choke		DC continuity, rejects common mode noise	Permits low-frequency ground loops	
Balanced circuit differential amplifier		Noise couples equally to both wires. CMR rejects noise	AC isolation limited. DC isolation lost with power OFF Common mode rejection decreases with frequency.	Not generally recommended
Line-driver/ receivers	RS-422 sending / RS-422 receiving	Established interface standard	Possible lack of common mode noise immunity; possible lack of isolation if power is off	Generally an acceptable interface design solution
Transmission lines	Properly terminated circuits	Minimize noise coupling	Not really isolated	Use with multi-point grounding

4.4 Grounding of Support Equipment. Support equipment used for testing the spacecraft should be constructed to maintain the grounding architecture for the spacecraft. In general, all interfaces between flight hardware and support equipment should be isolated.

4.5 Heritage Spacecraft. Spacecraft programs studied to establish these guidelines include those listed in Table V.

TABLE V. System Grounding and Isolation Used in Various Spacecraft

Space-craft	Power System Type/Voltage	Primary Power Ground Type	Primary Power Isolation to Structure/Resistance and Capacitance	Ground Type, Signal	Ground Type, Pyro	In-flight Grounding/Isolation Problems
Mariner-2 (1962)	Solar arrays/batt. 30 V dc; 50 V rms, 2.4 kHz ac	Rtn to Structure	N/A	Single ground reference with isolated IF's	Switched from battery	Short to Str, one solar array
Viking'75 Orbiter (1975)	Solar arrays/batt. 50 V ac; 30 V dc	Isolated from structure	ac 47 k-ohm to str, each line; dc 3k-ohm paralleled with 0.01 uF on return to structure	Single ground reference with isolated IF's	Isol. 5k ohm and 0.1 uF to Str.	Inverter failed at Lander release pyro event
Voyager (1977)	RTG 30 V dc; 50 V rms, 2.4 kHz ac	Balanced to structure	ac 47 k ohm and dc 10 k ohm symmetrically isolated and 0.1 uF dc return to structure	Single ground reference with isolated I/F's	Isol. 5k ohm and 1 uF to Str.	False telemetry readings at pyro fire: cause: 1 uF
Seasat (1978)	Solar arrays and battery	Isolated from structure	?	SPG each assy; IF's not isolated	?	Slip ring short hi to low may be fail cause at 6 months
Magellan (1989)	Solar arrays/batt. 28 V dc; 50 V rms, 2.4 kHz ac	Balanced to structure	ac 47 k ohm and dc 2 k ohm symmetrically isolated & 0.1uF dc return to structure	Single ground reference with isolated I/F's	Isol. 5k ohm and 0.1 uF to Str.	Anomaly after SRM casing release pyro event
Galileo (1989)	RTG 30 V dc; 50 V rms, 2.4 kHz ac	Balanced to structure	ac 47 k ohm and dc 2 k ohm symmetrically isolated & 0.1uF dc return to structure	Single ground reference with isolated I/Fs	Isol. 5k ohm and 0.1 uF to Str.	Slip ring leak, pwr to chassis (acceptable)
Hubble (1990)	Solar arrays and battery / 28 V dc	SPG Rtn to structure	True star ground, with very long wires (Note: very poor ac ground)	Multipoint; str. currents for signals	N/A (No pyro)	Solar array blanket may have caused in-flight grounding problems
Mars Observer (1992)	Solar arrays and battery / 28 V dc/10 V dc	Rtn to structure with 2 SPG's	N/A	Multipoint; str currents for signals	Rtn to Str	100% loss; cause unknown; during pyro event
TOPEX (1992)	Solar arrays and battery / 28 V dc	Rtn to structure	N/A	Single gnd ref, w/ isolated IF's	Switched from battery	None
NOAA-13 (1993)	Solar panels and battery	Rtn to structure	N/A	Multipoint; str. currents for signals	Rtn to Str.	Hi-side short to Str 1 mo after launch. 100% loss
Cassini	RTG / 30 V dc	Balanced to structure	2 k ohm each, high side and return to structure; 0.1 uF Rtn to Str	Single ground reference with isolated I/Fs	Isol. 5k ohm dc and ac	Sch. 1997 launch. See appendix A

NOTES: Rtn: return; Str: structure; some cells may be left empty due to lack of applicability ("N/A") or lack of knowledge ("?")
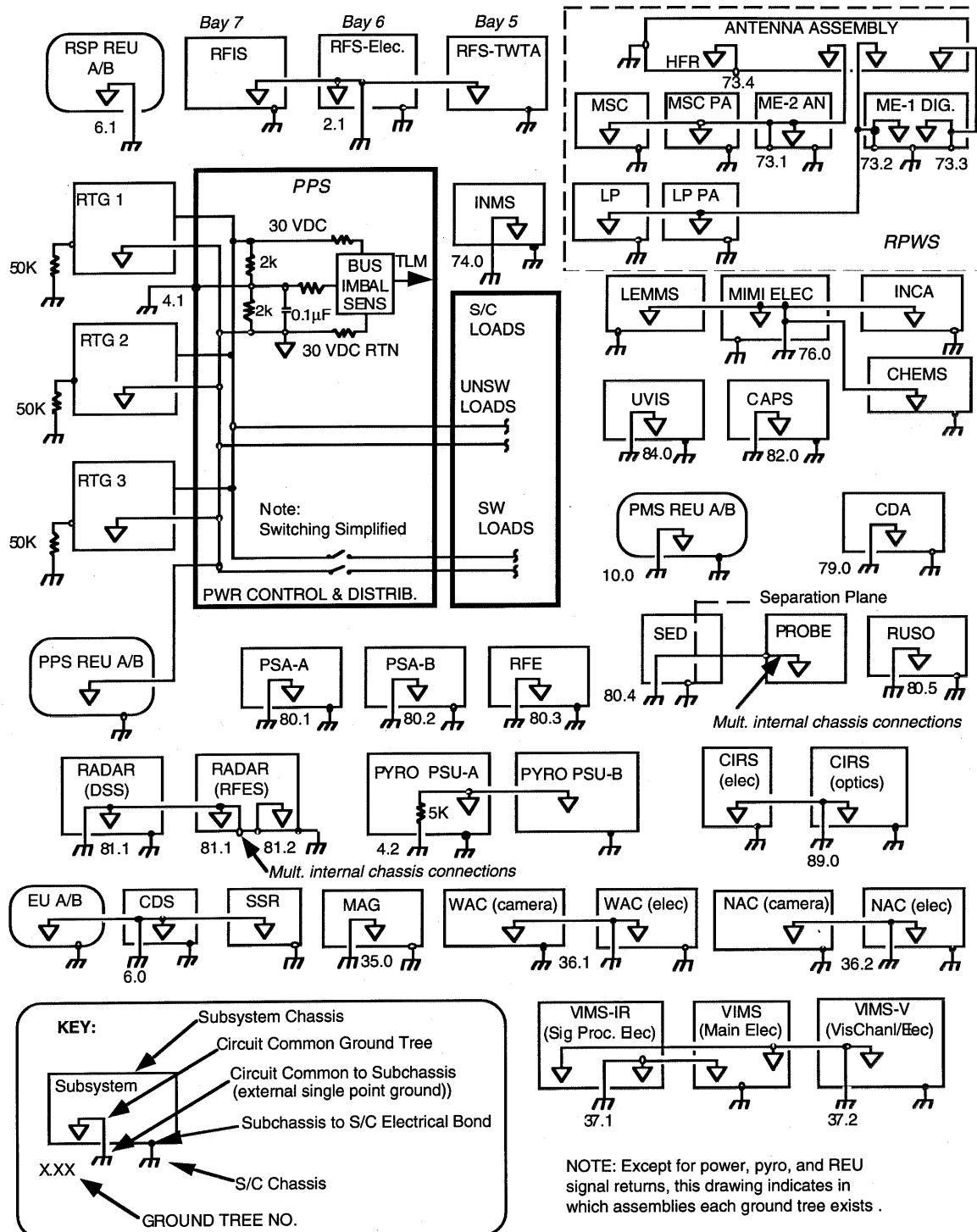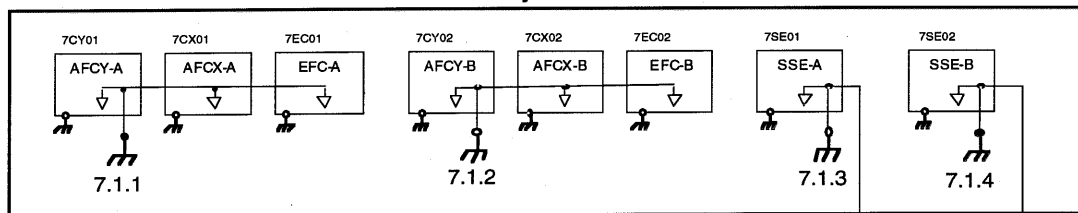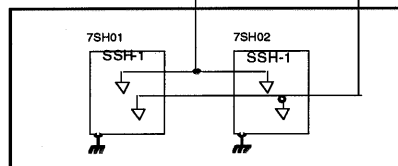
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APPENDIX A

SAMPLE GROUND TREES FOR LARGE COMPLEX SPACECRAFT
(PAGE 1 OF 2)

NOTE: Except for power, pyro, and REU signal returns, this drawing indicates in which assemblies each ground tree exists .

FIGURE 3-260:-02, CASSINI GROUND TREES, Page 1 of 2

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APPENDIX A
SAMPLE GROUND TREES FOR LARGE COMPLEX SPACECRAFT
(PAGE 2 OF 2)

Bay 1

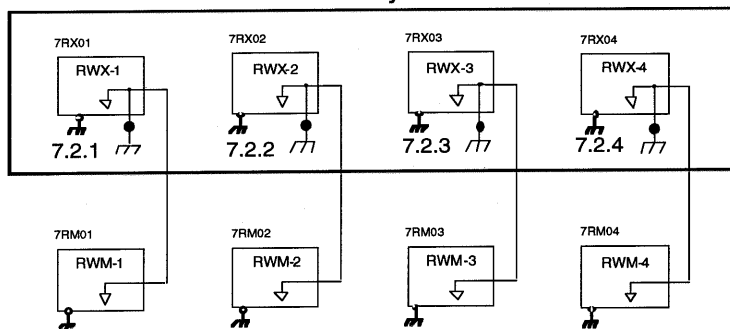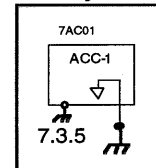| 7CY01	7CX01	7EC01	7CY02	7CX02	7EC02	7SE01	7SE02
AFCY-A	AFCX-A	EFC-A	AFCY-B	AFCX-B	EFC-B	SSE-A	SSE-B

7.1.1   7.1.2   7.1.3   7.1.4

NOTE: Except for power, pyro, and REU signal returns, this drawing indicates in which assemblies each ground tree exists .
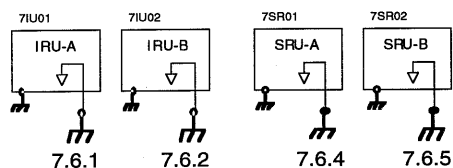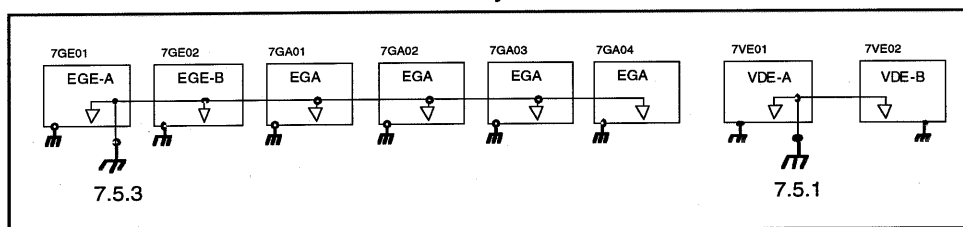
HGA

7SH01	7SH02
SSH-1	SSH-1

Bay 10

7RX01	7RX02	7RX03	7RX04
RWX-1	RWX-2	RWX-3	RWX-4

7.2.1   7.2.2   7.2.3   7.2.4

Bay 12

7AC01
ACC-1

7.3.5

7RM01	7RM02	7RM03	7RM04
RWM-1	RWM-2	RWM-3	RWM-4

Bay B

7GE01	7GE02	7GA01	7GA02	7GA03	7GA04	7VE01	7VE02
EGE-A	EGE-B	EGA	EGA	EGA	EGA	VDE-A	VDE-B

7.5.3   7.5.1

7IU01	7IU02	7SR01	7SR02
IRU-A	IRU-B	SRU-A	SRU-B

7.6.1   7.6.2   7.6.4   7.6.5

AACS Ground Trees

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